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Temperature dependence of quantum lifetime in *n*-InGaAs/GaAs structures with strongly coupled double quantum wells

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Longitudinal $\rho_{xx}(B)$ and Hall $\rho_{xy}(B)$ magnetoresistances are experimentally investigated as a function of in-plane and transverse magnetic fields in *n*-InGaAs/GaAs nanostructures with strongly-coupled double quantum wells in the temperature range $T = 1.8$–70 K and magnetic fields $B = 0$–9.0 T. Experimental data on the temperature dependence of quantum lifetime in diffusive ($k_BT/\tau_{tr} \ll 1$) and ballistic ($k_BT/\tau_{tr} \gg 1$) regimes are reported. It has been found that in the ballistic regime in the temperature range where $k_BT/E_F < 0.1$, the observed quadratic temperature dependence of quantum lifetime is determined by inelastic electron–electron scattering. However, the temperature dependence of quantum lifetime cannot be quantitatively described by the existing theories in the whole temperature range. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4775751]

1. Introduction

Two fundamentally new and extremely important properties have been found in the energy spectrum of two-dimensional (2D) electron gas. First, the spectrum is discrete and, second, the electron motion becomes coherent (the wave function possesses a well-defined phase and quantum interference effects arise) unless the charge carriers experience inelastic scattering in the course of propagating from one end of the sample to another. The electron scattering by ionized impurities, boundaries roughness, and electrons themselves modifies significantly these properties. In particular, inelastic electron–electron scattering leads to broadening of the discrete energy levels and dephasing of the wave function, and, as a result, to the breakdown of interference (quantum) effects: the 2D electron gas becomes quasi-classic. This can play an important role in certain cases.

The temperature dependence of electron-electron scattering is not universal and is defined by the dimensionality of the electron system, degeneracy degree of electron gas, type of scattering potential, characteristic of screening, and specific aspects of a particular sample. In praxis, this dependence manifests itself in the temperature dependence of two particular times: quantum life time $\tau_q(T)$ and the time of inelastic scattering or dephasing τ_φ. Experimental determination of these times in different temperature regimes as well as their dependence on characteristic aspects of specific nanostructures is the main instrument for studies of electron–electron scattering.

Quantum lifetime is typically determined by analyzing the magnetic field dependence ($B_\perp^{-1}$) of the peak amplitudes in Shubnikov-de Haas (SdH) oscillations. It is well known that the SdH oscillations suitable for analysis can only be obtained at temperatures below 4.2 K. At such low temperatures, the contribution due to inelastic electron-electron scattering mechanisms vanishes since $E_F \gg k_BT$ and $\hbar/\tau_q^{e-e}(T) \approx (k_BT)^2/E_F$, so τ_q^{e-e} can be considered temperature-independent (here, E_F is the Fermi energy, k_B is the Boltzmann constant, and τ_q^{e-e} is the quantum lifetime due to electron-electron scattering). Therefore, this standard method is absolutely unsuitable for determining $\tau_q^{e-e}(T)$. Currently an intensive search is on for new experimental techniques which could allow determining $\tau_q^{e-e}(T)$. The most promising are the techniques involving studies of various quasi-2D structures. For instance, in single quantum wells with two completely filled subbands of spatial quantization, a new type of magnetoresistance oscillations has been found, so-called magneto-intersubband oscillations,[1] which can be observed at high temperatures, where the SdH oscillations do not exist. The temperature dependence of the oscillation amplitude is determined by the temperature dependence of the Landau levels widths $2\hbar/\tau_q(T)$ and, therefore, $\tau_q^{e-e}(T)$. Even more promising, in our view, are the quasi-2D structures with double quantum wells (DQW), in which the tunneling effects between the wells are directly related to broadening of the electron energy levels.

The presence of additional degrees of freedom in the quasi-2D systems containing two DQW coupled via tunneling leads to the whole range of new interesting magneto-transport phenomena,[1–20] which are currently intensively studied using various kinetic methods. In particular, in zero magnetic field and under condition of equal charge carrier concentration in the wells (balance) and asymmetric scattering (charge-carrier mobilities differ in different wells), resonant resistance is observed.[15] In parallel magnetic field $B_\parallel$ this resonant resistance is suppressed. It is well known that the presence of a dependence on $B_\parallel$ is the measure of quasi-twodimensionality. The intensity of the effect is determined by the value of tunnel gap Δ_{SAS} and broadening of the energy levels in the wells $\hbar/\tau_q$ and, therefore, also by the quantum lifetime.[15] Measurements on the structures with DQW in parallel magnetic fields in the temperature range corresponding to the ballistic regime can determine both the tunneling gap and $\tau_q(T)$. Analysing τ_q

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allows to obtain the information on particular aspects of inelastic electron-electron scattering in quasi-2D systems.

Nevertheless, despite the achievements reached by new techniques, the problem of significant discrepancy between theory and experiments remained unsolved. Several experiments have exhibited not only quantitative discrepancies with theory (by an order of magnitude) but also qualitative disagreement. Several possible reasons for that are currently discussed in literature.[8–19] In particular, the quasi-2D systems used in experiments are not yet sufficiently "ideal": the parameters of real structures do not satisfy the conditions built into various approximations within the frame of Fermi-liquid theory. For example, the concentrations of charge carriers in the structures currently used in electronics as well as in experiments are rather low. Upon discussing the observed discrepancies between the experimental data and theory predictions, it has been suggested that the interacting electron gas in such structures cannot be treated as a Fermi-liquid. Below we will discuss further reasons for these discrepancies.

2. Theoretical dependence of quantum lifetime on temperature

It is well known that the temperature dependence of charge carrier lifetime $\tau_q(T)$ in semiconductor structures is the result of inelastic electron-electron scattering $\tau_q^{e-e}(T)$. As follows from simple physical reasoning, the temperature dependence of the time between electron collisions is governed by two contributions. The first, which is the most important one, is the Pauli principle limiting the phase space of electron-electron interaction. The second one is due to screening of the Coulomb interaction between the electrons.[2–13] The influence of the Pauli principle in 2D-case is accounted for by the term $A(k_BT/E_F)^2\ln(E_F/(k_BT))$ in Eq. (1), which represents the first-order approximation of the Coulomb interaction. Accounting for higher orders and screening of electron-electron interaction also lowers the cross-section of electron-electron scattering. In the models employed to obtain the theoretical dependences of $\tau_q^{e-e}(T)$, two channels of electron-electron scattering, singlet and triplet, have to be considered in two temperature regimes (diffusive $k_BT/\tau_{tr} \ll 1$ and ballistic $k_BT/\tau_{tr} \gg 1$).[8] However, all theoretical studies so far are, as a rule, focused only on particular aspects of this problem. In the great majority of the theoretical work, the consideration is limited to only the singlet channel of electron-electron scattering: in the diffusive regime in Refs. 2 and 3 and in the ballistic regime in Refs. 4–6 and 8–13. The ballistic regime in the triplet channel has only been considered in Ref. 7. Moreover, these studies have been mainly devoted to the quest for universal contributions, not dependent on the specific parameters of real electron systems (dimensionality, degree of disorder, and specific aspects of screening). Besides that, the theoretical models apply various approximations (e.g., perturbation theory, random-phase approximation, Fermi's golden rule), which are not necessarily fulfilled in experiments.

For an ideal 2D-system, the theoretical temperature dependence of the inverse quantum lifetime (the rate of electron-electron scattering) in the singlet channel in ballistic regime has been obtained since more than 40 yr ago in a well-known and most cited paper by Giuliani and Quinn:[3]

$$\frac{\hbar}{\tau_q^{e-e}}(T) = \frac{E_F}{2\pi}\left(\frac{k_BT}{E_F}\right)^2\left[\ln\left(\frac{E_F}{k_BT}\right) + \ln\left(\frac{2q_{TF}}{k_F}\right) + 1\right]. \quad (1)$$

In the dirty-metal limit, Fukuyama and Abrahams[4] have also obtained the temperature dependence of electron-electron scattering rate in the singlet channel in diffusive and ballistic regimes. The influence of disorder was accounted for in the first order of perturbation theory. Additionally, they have assumed that the Thomas-Fermi wave vector $q_{TF} \gg 2k_F$

$$\frac{\hbar}{\tau_q^{e-e}}(T) = \frac{\pi E_F}{2}\left(\frac{k_BT}{E_F}\right)^2\left[\ln\left(\frac{E_F}{k_BT}\right)\right] \quad \text{at} \quad k_BT/\tau \gg 1, \quad (2a)$$

$$\frac{\hbar}{\tau_q^{e-e}}(T) = \frac{1}{2}\left(\frac{k_BT}{E_F\tau}\right)\left[\ln\left(\frac{E_1}{k_BT}\right)\right] \quad \text{at} \quad k_BT/\tau \ll 1. \quad (2b)$$

It can be seen that Eqs. (1) and (2a) differ from each other by a numerical coefficient ($\pi/2$ vs $1/2\pi$) amounting almost to one order of magnitude and the absence of non-logarithmic temperature-independent terms in square brackets.

Accounting for higher-order terms in the Coulomb interaction within a single layer of 2D-gas, reported in a theoretical paper by Reizer and Wilkins,[12] has led to a change in the numerical coefficient by $\pi/8$ and appearance of new logarithmic and non-logarithmic temperature-dependent terms in square brackets in Eq. (1)

$$\frac{\hbar}{\tau_q^{e-e}}(T) = \frac{\pi}{8}E_F\left(\frac{k_BT}{E_F}\right)^2 \times \left[\ln\left(\frac{4E_F}{k_BT}\right) - \ln\left(\frac{2p_F+\kappa}{\kappa+k_0}\right) - \frac{2}{(2p_F+k_0)}\frac{(2p_F-k_0)\kappa}{(\kappa+k_0)}\right], \quad (3)$$

where $\kappa = 2\pi e^2\nu/\chi$ and $k_0 = k_BT/v_F$. $\nu = m/\pi\hbar^2$ is the density of states, χ is the dielectric constant, and v_F is the Fermi velocity of electrons.

In a relatively recent Ref. 8, where dephasing processes have been theoretically investigated at arbitrary ratios of $\hbar/\tau$ and k_BT and taking into account renormalization in the triplet channel of Coulomb interaction, it has been shown that the dephasing time τ_φ at low temperatures $k_BT\tau/\hbar \ll 1 + F_0^\sigma$, where F_0^σ is the dimensionless constant of electron-electron interaction in the diffusive regime, is defined by the equation:

$$\tau_\varphi^{-1}(T) = \left[1 + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)(2+F_0^\sigma)}\right]\frac{\pi G_0 k_BT}{\hbar\sigma_D}\ln\left(\frac{k_BT\tau_\varphi}{\hbar}\right), \quad (4)$$

$$G_0 = 2\pi\hbar/e^2R.$$

In reality, this expression is an approximate one since it does not account for the contribution of ballistic effects to the phase relaxation rate as well as for its dependence on energy $\varepsilon \equiv E - E_F$. If these effects are accounted for, the temperature dependence of time τ_φ follows the expression:

$$\tau_\varphi^{-1}(T) = \left[1 + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)(2+F_0^\sigma)}\right]\frac{k_BTG_0}{\hbar\sigma_0}\ln\left(\frac{\sigma_0}{G_0}(1+F_0^\sigma)\right) + \frac{\pi}{4}\left[1 + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)^2}\right]\frac{k_B^2T^2}{\hbar E_F}\ln\left(E_F\frac{\tau}{\hbar}\right). \quad (5)$$

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At high temperatures, where the processes involving transfer of larger energy quantum dominate

$$\tau_{\varphi}^{-1}(T) = +\frac{\pi}{4}\frac{k_B^2 T^2}{B_{\text{coef}}\hbar E_F} \times \left\{ \ln\left(\frac{2E_F}{k_B T}\right) + \frac{3(F_0^{\sigma})^2}{(1+F_0^{\sigma})^2} \ln\left(\frac{E_F}{k_B T\sqrt{b(F_0^{\sigma})}}\right) \right\}. \quad (6)$$

Here $b(x) = (1+x^2)/(1+x)^2$, B_{coeff} is the numerical coefficient, which varies from 0.84 for weak magnetic fields ($\Omega_H \tau_{\varphi} \gg 1$, $\Omega_H = 4DeH/\hbar c$) to 0.79 in the opposite limit.

For quasi-2D systems—single quantum wells with two subbands of spatial quantization and balanced double quantum wells with the subbands of symmetric and asymmetric states, where electron-electron interaction takes place both within the subbands and between them—the expression for the temperature dependence of electron-electron scattering becomes significantly more complex. Before starting the investigation of, e.g., inelastic electron-electron scattering in quasi-2D semiconductor structures, at least two problems need to be solved.

1. As $\tau_q(T)$ is not directly measured in an experiment, a relation of the inverse time of inelastic electron-electron scattering with an experimentally measurable parameter of the investigated structure needs to be found. In particular, in our case, such a measurable parameter was the dependence of resonant resistance of the structure with balanced DQW on the magnetic field component $B_{\|}$ parallel to the sample plane in a wide temperature range. If the theoretical relation between the resonant resistance and τ_{φ} is known, then, by measuring the dependence and fitting it, $\tau_q(T)$ can be plotted. The theoretical dependence needs to take into account all the specific aspects of the experiment.
2. The equation relating the quantum lifetime $\tau_q(T)$ with the microscopic parameters of the sample should be obtained. There are a number of methods used in theory to obtain such equations. In particular, in quantum physics, Fermi's golden rule allows to calculate the probability of transition between two states of a quantum system by using time-dependent perturbation theory. The probability of transition per unit time is inversely proportional to the lifetime of the state.

Several theoretical[9–13] and experimental[15–18] studies have been devoted to solving this problem for structures with DQW (only Ref. 15 has considered strongly coupled DQW). The whole range of new factors need to be considered in quasi-2D structures: intra- and inter-subband scattering, the ratios of sample geometrical parameters (the widths of well and barrier, the distance to the dopants in the barriers), the size of tunneling gap, the concentration balance, and degree of scattering symmetry, i.e., charge carriers mobility in quantum wells.

Accounting for higher order terms in the expansion, the following expression has been obtained in the theoretical work by Reizer and Wilkins[12]

$$\frac{\hbar}{\tau_q^{e-e}}(T) = \frac{\pi E_F}{32}\left(\frac{k_B T}{E_F}\right)^2 \left\{ [(1+2\kappa b)^2+2]\ln\left(\frac{2E_F}{k_B T}\frac{pb}{p_F b}\right) - \ln\left(\frac{pb+2\kappa b(1+\kappa b)}{k_0 b+2\kappa b(1+\kappa b)}\right) - \frac{4[(1+2\kappa b)^2+1]\kappa b(pb-\kappa_0 b)(1+\kappa b)}{[pb+2\kappa b(1+\kappa b)][\kappa_0 b+2\kappa b(1+\kappa b)]} \right\}, \quad (7)$$

where $pb = \min(2p_F b, 1)$, $k_0 = k_B T/v_F$, $\kappa = 2\pi e^2 \nu/\chi$, v_F is the Fermi velocity of electrons, and χ is the dielectric constant.

3. Experimental results and discussion

The samples of *n*-InGaAs/GaAs with strongly coupled DQW in which the conduction occurred through the subbands of symmetric (S) and asymmetric (AS) states separated by a tunneling gap ($\Delta \geq 3.0$ meV) were investigated. The *n*-InGaAs quantum wells with the width $d_W = 5$ nm were separated by a GaAs barrier with the thickness $d_B = 10$ nm. The structures were symmetrically doped with Si in the barriers ($N_D = 10^{18}$ cm^{-3}). The regions of electron transport and doping were separated by the distance equal to the spacer widths $d_S = 190$ nm.[4] The measurements of the resistance tensor components $\rho_{xx}(B,T)$ and $\rho_{xy}(B,T)$ were carried out in the temperature range $1.8\,\text{K} \leq T \leq 70\,\text{K}$ in tilted magnetic fields $B(B_{\|}, B_{\perp})$ upon detailed scanning of the plane $(B_{\|}, B_{\perp})$ over the entire circle from the highest value of magnetic field down to zero. This was achieved by using a precise electronically-controlled programmable rotator (Quantum Design Inc.), which allowed varying the angle of magnetic field relative to the normal to the layers with an angular step size of 0.1°. The set of obtained curves $\rho_{xx}(B,T)$ and $\rho_{xy}(B,T)$ was plotted as solid surfaces $\rho_{xx}(B_{\perp}, B_{\|})$ and $\rho_{xy}(B_{\perp}, B_{\|})$ using a special interpolation program. One of such surfaces at $T = 1.8$ K is presented in Fig. 1. It was such surfaces that were used to numerically make cross-sections

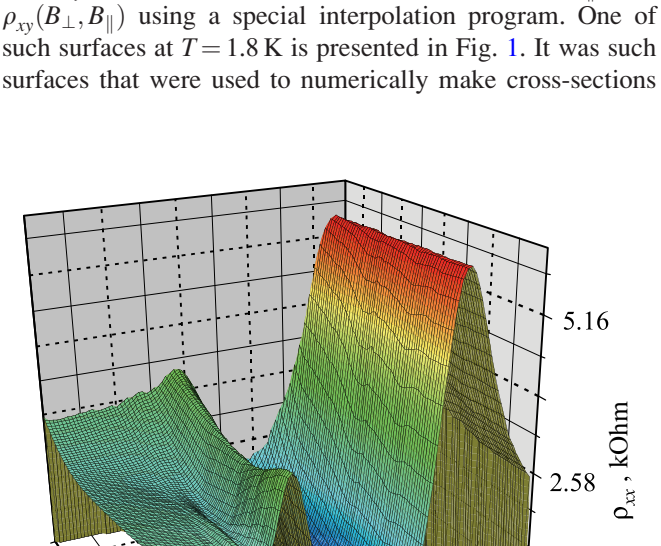

FIG. 1. Dependences of the sample magnetoresistance $\rho_{xx}(B_{\perp}, B_{\|})$ (3D plot) on in-plane and transverse magnetic fields at the temperature $T = 1.8$ K.

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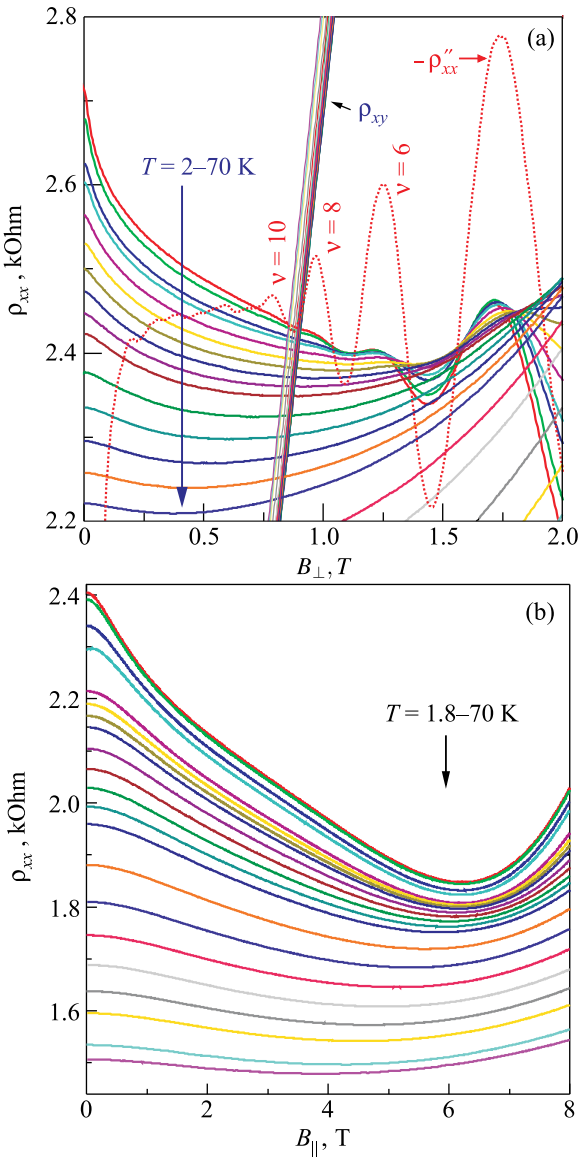

FIG. 2. Dependences of $\rho_{xx}(B_\perp, T)$ and $\rho_{xy}(B_\perp, T)$ at different temperatures in the transverse magnetic field (a) and $\rho_{xx}(B_\parallel, T)$ in the in-plane magnetic field (b).

of the dependences $\rho_{xx}(B,T)$ and $\rho_{xy}(B,T)$ with one of the components, $B_\perp$ or $B_\parallel$, varying and another one fixed for further analysis of the obtained dependences $\rho_{xx}(B_\perp, T)$ and $\rho_{xx}(B_\parallel, T)$. Figs. 2(a) and 2(b) show the dependences $\rho_{xx}(B_\perp, T)$ and $\rho_{xx}(B_\parallel, T)$. It can be seen that negative magnetoresistance (NMR) is observed both in transverse and in-plane magnetic fields.

Early experimental studies of inelastic electron-electron scattering has been focused on measuring the dephasing time $\tau_\varphi(T)$. It is well known that the NMR in $B_\perp$ is related to suppression of the quantum effects of weak localization. Analyzing the NMR dependence at different temperatures allows to obtain the temperature dependence of the inelastic scattering time $\tau_\varphi(T)$. Recently, however, the preference goes to the techniques investigating the temperature dependences of tunneling effects between two quantum wells, which are entirely determined by the extend of energy level broadening in the quantum wells. The energy level broadening is characterized by the quantum lifetime τ_q. In this study, we will only analyze the NMR temperature dependences obtained in in-plane magnetic field.

It was found that in our investigated structures, the mobilities in the subbands of A and AS states $\mu_{S,AS}(T)$ not only have the different values, but also exhibit different temperature dependences. $\mu_S(T)$ had a "dielectric" character $(d\rho/dT < 0)$, while $\mu_{AS}(T)$ showed "metallic" behavior $(d\rho/dT > 0)$. As a result, the difference in mobility grows with T increasing that inevitably leads to the appearance of resonant resistance.[15]

It is well known that in the structures with DQW a so-called resonant resistance[15] can arise due to the difference in mobilities in balanced quantum wells, when they have equal charge carrier concentrations. In-plane magnetic field significantly modifies the energy spectrum of the DQW structure and suppresses tunneling between the wells.[15] As a result, the resonant resistance is suppressed as well. The rate of this suppression strongly depends on temperature, which is related to the temperature dependence of the quantum lifetime $\tau_q(T)$. Upon increasing temperature, the peaks in the experimental curves $\rho_{xx}(B_\parallel, T)$ broaden, which is related to decrease in τ_q with increasing temperature.

In Ref. 15, the following expression for the resistance in $B \parallel k_y$ has been obtained:

$$\rho_{xx}{}^{-1}(B) - \rho_{\text{off}}^{-1} = [\rho_{xx}(0)^{-1} - \rho_{\text{off}}^{-1}] f(B/B_c), \qquad (8)$$

where $f(x) = 2[(1+x^2)^{-0.5} - 1]x^{-2}$ and ρ_{off} is the minimal resistance, which corresponds to DQW leaving the resonance. The characteristic magnetic field B_c is equal

$$B_c = \frac{\hbar}{e} \frac{1}{\nu_F \tau_q b} \sqrt{1 + \left(\frac{\Delta_{SAS}}{\hbar}\right)^2 \left(\frac{\tau_{\text{tr}}^1 + \tau_{\text{tr}}^2}{2} \tau_q\right)}, \qquad (9)$$

where $2\tau_q^{-1} = \tau_{q1}^{-1} + \tau_{q2}^{-1}$.

Based on the analysis of DQW in transverse magnetic field at temperatures below 8 K, Hall effect in weak $(R_H(B,T))$ and strong magnetic fields, as well as positive magnetoresistance in transverse magnetic field[17] at $T \geq 20$ K, we determined the concentrations, mobilities and transport relaxation times of charge carriers in the subbands of S and AS states $(n_{S,AS}(T),\ \mu_{S,AS}(T),\ \tau_{tr}^1(T),\ \tau_{tr}^2(T))$ and the Fermi energies $(E_{F_S} - E_{F_{AS}} = \Delta_{SAS})$ (Ref. 17). The total electron concentration $n_T = n_S + n_{AS} = 2.27 \cdot 10^{11}\ \text{cm}^{-2}$ was determined by analyzing the peak and plateau positions in the quantum Hall effect, the effective mobility was $\mu_T = 1.15 \cdot 10^4\ \text{cm/V s}$. By analyzing the activation dependence of the longitudinal resistance $\rho_{xx}(B_\perp, T)$ in the minima in the quantum Hall regime, the value of tunneling gap $\Delta_{SAS} \approx 3.0$ meV was obtained.[17]

As can be seen from Eq. (9) for B_c, τ_q is the only fitting parameter there. We carried out fitting of NMR data for in-plane magnetic field at temperatures up to 70.0 K. Some examples of it are shown in Fig. 3. This allowed us to obtain $\hbar/\tau_q(T)$ dependence and then also $\hbar/\tau_q^{e-e}(T)$. The $\hbar/\tau_q^{e-e}(T)$ dependence obtained by us is shown in Fig. 4 as "★." The same figure demonstrates the experimental results of Ref. 18 as well as several theoretical curves (see the figure caption). It can be seen that $\hbar/\tau_q^{e-e}(T)$ dependence obtained by us significantly differs (both quantitatively and qualitatively) from the others. First, this dependence is non-monotonous and, second, at $k_BT/E_F < 0.1$ the numerical values of electron-

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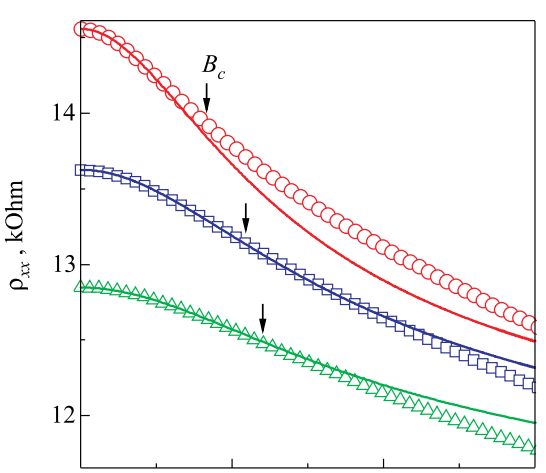

FIG. 3. Dependences of $\rho_{xx}(B_\parallel, T)$ on in-plane magnetic field at different temperatures T, K: 3 (○), 8 (□), and 14 (△). Symbols denote the experimental data; solid lines correspond to the theoretical model of Ref. 15. Arrows indicate the determined value of critical field B_c (see Eq. (9)).

electron scattering rate exceed all experimental as well as theoretical data by other authors.

It is known[18] that the quantum lifetime τ_q is determined by three electron scattering mechanisms. Scattering on ionized impurities τ_q^{e-imp} is elastic and does not depend on T. Two other scattering mechanisms—on phonons (τ_q^{e-ph}) and electrons on electrons (τ_q^{e-e})—are temperature dependent:

$$(\tau_q)^{-1} = (\tau_q^{e-\mathrm{imp}})^{-1} + (\tau_q^{e-\mathrm{ph}}(T))^{-1} + (\tau_q^{e-e}(T))^{-1}.$$

At low temperatures, the contribution $(\tau_q^{e-e})^{-1}$ is proportional to $k_BT/E_F \ll 1$ and therefore vanishingly small; the contribution $(\tau_q^{e-imp})^{-1}$ dominates. For scattering by remote impurities (low-angle scattering in nanostructures with a spacer)

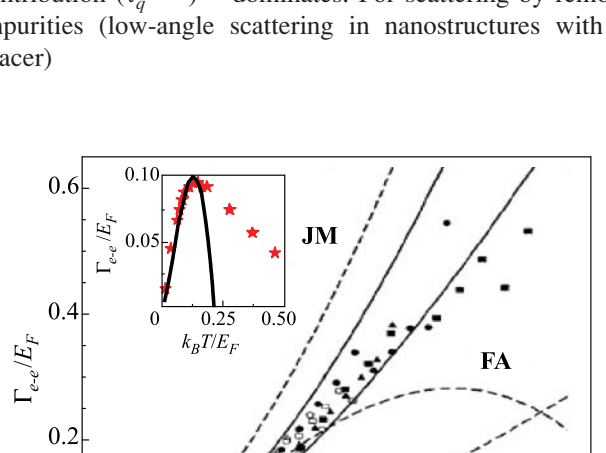

FIG. 4. Temperature dependence of the quantum lifetime. Dashed lines show the theoretical dependences: **GQ**[3] ($A = 1$); **FA**[4] ($A = \pi$); **JM**[9] ($A = \pi^2/2$). Solid lines correspond to the theoretical dependence given by Eq. (1), symbols are the experimental data from Ref. 18 ($A = 3.06 \pm 0.09$). The experimental data obtained in the present paper are shown as (★) ($A = \pi^2$). The insert shows the results of fitting the experimental data obtained in this work to the theoretical expression (1),[3] solid line.

$$\frac{\hbar}{\tau_q^{e-\mathrm{imp}}} = \frac{\hbar^2 n_D}{2m^* s}\sqrt{\frac{\pi}{2}}n^{-0.5},$$

where n_D is the impurities concentration and s is the spacer width; $4k_Fds \gg 1$ (for our samples $4k_Fds \approx 10$). As was shown in the papers by Gold,[14] in the case of electron-phonon scattering, the contribution $(\tau_q^{e-ph})^{-1}$ is comparable with $(\tau_{tr})^{-1}$ and therefore can be found from the temperature dependences of mobility. Since the quantum lifetime in the structures with selective doping (with a spacer) is significantly shorter than the transport relaxation time, the following expression can be written for the scattering rates:

$$(\tau_q^{e-\mathrm{ph}}(T))^{-1} \approx (\tau_{\mathrm{tr}})^{-1} \ll (\tau_q^{e-e}(T))^{-1}.$$

Therefore, it can be assumed that the obtained temperature dependence of the quantum lifetime is related to the temperature dependence of electron-electron scattering $\tau_q^{e-e}(T)$. It can be clearly seen in Fig. 4 that the dependence obtained by us is non-monotonous. The characteristic quadratic dependence is only observed at low temperatures ($k_BT/E_F < 0.1$). A qualitative disagreement with the presented theoretical dependences is also clearly visible. Let us discuss possible origins of qualitative as well as quantitative discrepancies between our data and the theoretical predictions.

As was already mentioned in Sec. 1, there is not a single theoretical work that could describe existing experimental data with a reasonable accuracy. Apparently, no universal temperature dependence of electron-electron scattering in 2D structures (as, for example, for the quantum Hall effect) exists. Everything is determined by specific aspects of a particular experimental situation.

All theoretical dependences of $\hbar/\tau_q^{e-e}(T)$ known to us[3–13] (see Sec. 2) can be represented in the following form:

$$y = Ax^2(-\ln x + \ln B \pm C), \qquad (10)$$

where the argument is $x = k_BT/\varepsilon_F$. The coefficients A, B, and C are attributed by different authors to different electron-electron interaction mechanisms, screening, as well as specific aspects of a particular electronic structure and, therefore, have a different analytical form. It can be easily seen that this dependence has an extremum at certain ratios of the parameters. The extremum position depends significantly on parameters B and C, while its amplitude is defined by parameters A and C.

The coefficient A is determined by the calculation method and the assumption used. Its value reported by different authors differs a lot. For instance, in Ref. 10 $A = \pi/4$, in Refs. 2 and 3 $A = 1/(2\pi)$, in Ref. 4 $A = \pi/2$, and in Ref. 9 $A = \pi^2/2$ (see figure caption in Fig. 4). In the studies reported by Reizer and Wilkins,[12] accounting for higher-order terms has led to the value of $\pi/8$.

For example, in Ref. 18, as a result of treatment of more than 300 experimental dependences, it has been found that in order to match the experimental data with the widely accepted theory of Ref. 3, a coefficient $A = 3.06 \pm 0.09$ should be added to Eq. (1). All theoretical dependences

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shown in Fig. 4, which was adopted from Ref. 18, differ from each other only by the value of the coefficient A. In particular, for our experimental data to match quantitatively the theory of Ref. 3, the coefficient A should be equal to π^2. The values of A in quoted references are reported in the figure caption of Fig. 4. Evidently, the difference grows with increasing k_BT/E_F. Several reasons for different values of the coefficient A can be named. First, all the theories are based on the assumption of smallness of the energy of an excited electron participating in a scattering event, as compared to the Fermi energy, $k_BT/E_F \ll 1$. The authors of Ref. 11 have suggested that the requirement $\ln(E_F/k_BT) \gg 1$ is more relevant. Second, at the same temperature, k_BT/E_F grows with decreasing concentration, which leads to increase in system disorder and difficulties in fulfilling the assumptions on which the mentioned theoretical works are based. Third, there is no consensus up to know on how inter-subband and electron-electron exchange scattering in quasi-2D structures should be accounted for.

With regard to the coefficients B and C, the situation is equally ambiguous. The form of the second and third terms in Eq. (10) is determined by the specific aspects of screening effects and details of particular experimental structures.

We carried out fitting of the experimental data (see insert in Fig. 4) to Eq. (10). Apparently, it was possible to describe the position and amplitude of the maximum with the following values of parameters: $A = 10$, $B = 0.1$, and $C = 0$. It should be noted that $B = 2q_{TF}/k_F = 0.1$ (according to Eq. (1)). However is does not reflect the actual physical situation since for 2D electron gas in real nanostructures with low density of charge carriers, the wave vector of Thomas-Fermi screening is large than the Fermi wave vector ($B > 1$). On the other hand, it can be easily seen that the experimental dependence can be also described by the following equation:

$$y = Ax^2\left[\ln\left(\frac{1}{x}\right) + \ln\left(B + e^{\pm C}\right)\right]. \qquad (11)$$

Therefore, for every value $B > 1$, a value $C < 0$ can be found.

As mentioned earlier, the additional terms in square brackets account for specific aspects of a particular electronic systems and experimental technique. We consider here the samples of the nanostructures containing two strongly coupled quantum wells. In this case, the specific properties are determined by ratios of the following parameters: transport relaxation time τ_{tr}, quantum lifetime τ_q, dephasing time τ_φ, inter-subband scattering time $\tau_{12,21}$, distance between the centers of quantum wells b, screening length ξ equal to one half of the Bohr radius $a^B/2$, as well as the ratios k_BT/E_F and Δ_{SAS}/k_BT. In the limiting cases $b = \infty$ or even $b \gg \xi$, the double quantum well can be considered as two independent wells (in this case $\tau_{12} = \tau_{21} \gg \tau_q$, $\hbar/(k_BT)$). Therefore the rate of electron-electron scattering in DQW is just the sum of the rates in individual quantum dots. The temperature dependence of the quantum lifetime $\tau_q^{e-e}(T)$ can be analyzed using the theoretical models and expressions (1)–(7).

In another limiting case $b = 0$ or $b \ll \xi$, the DQW can be considered as a single quantum well and $\tau_{12} = \tau_{21} \ll \tau_q$, $\hbar/(k_BT)$. In this case, the electron subsystem is four-fold degenerate (with respect to spin and pseudospin), similar to spin and valley degeneracy in n-SiMOSFET structures. Accounting for electron-electron interaction in 15 triplet channels in ballistic regime becomes complicated, even at equal concentrations ($n_1 = n_2$) and mobilities ($\mu_1 = \mu_2$). Experimentally, the limit $b/\xi \leq 1$ is pretty much (at least nowadays) unreachable.

In an experiment, we deal, as a rule, with an intermediate case. For our structures $b \geq 3\xi$ and the concentrations and mobilities in the wells are different. Therefore, the theoretical results of Ref. 20 cannot be applied to our case. The analytical expressions for logarithmic temperature-dependent terms in curved brackets in Eq. (7) (Ref. 12) cannot be represented in the form of Eq. (11) as required.

4. Conclusion

The temperature dependences of quantum lifetime in n-InGaAs/GaAs were measured in the temperature range 1.8–70 K using the technique of measuring NMR in this temperature range in in-plane magnetic field. It was shown that this technique is more promising then measuring SdH oscillations for the purposes of investigating the temperature dependences of quantum lifetime and inelastic electron-electron scattering in quasi-2D structures with DQW. We suggested and discussed possible origins of both quantitative and qualitative discrepancies between the experimental and theoretical temperature dependences of electron-electron scattering in the entire temperature range. The obtained dependence of $\tau_q^{e-e}(T)$ cannot be described by existing theories.

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